As Mohamed said, I will be discussing the mission and vehicle integration trades and so I am not going to say anything about reactors, neutronics or anything else. The issue here is that you can make a reactor or an engine, but unless you can hang it into a vehicle it won't go anywhere. So I would like to address some of these issues.

You have to go through all of these factors (Figure 1) before you know if the vehicle can fly. You have to look at the whole vehicle. You can have all kinds of efficiencies you want in the reactor, but if it doesn't fly, it won't go anywhere.

Here are some of the trades done back then during the NERVA program (Figure 2). What shape is your tank and where do you put your rocket engine and your reactor? You go in with some distance to avoid the radiation (this will cause feed system problems), then you begin to play with geometry; the optimum that came out is a 15 degree cone angle.

Figure 3 shows the mass and radiation breakdown for the shielding from the previous chart that I showed you. The 15-degree cone angle gives you the lowest radiation for a given shield mass. So, based on this chart it was decided that we would pick the 15-degree cone angle as the bottom of the tank.

There were many other trades that were done. Here is what the problem looked like; you are not going to Mars and get rid of the reactor, you are going to fire it, shut it down, and then you have to cool it. When you use propellant as coolant, you lose specific impulse. The trades done back then show what happens to your specific impulse as you cool the reactor down (Figure 4). So you have to go through these trades as well.

As to radiation maps (Figure 5), I am not a radiation expert, but these were done back for the NERVA engine. You have neutron flux, you have gamma radiation, a reference point up there and we are talking about a 1575 megawatt reactors operating for 53 minutes and so on. So all these factors have to be addressed.

Then as to what happens after shut down (Figure 6), you have a decay which goes as shown, and here is the radiation versus distance, which continues on, and so on.
In our present studies (Figures 7-9) we are moving from the 1960’s to the 1980’s and 1990’s via computer programs. We had a very good correlation between the calculations from the old NERVA data that we got out of the design handbooks. The same thing was found for a small engine that was supposed to operate an ROTV out of the space shuttle, (if you can believe that) (Figure 7).

For a pellet bed reactor mission to Mars, just the other day one of our guys gave me these numbers (Figure 10). If you fly on May 11, 2018, taking 250 days for the total trip, with 30 days stay, these are your Delta-V breakdowns. So on the basis of this, we can take a thrust, an engine, and hang it on the vehicle and start calculating some system masses and see what happens.

This is what happens when you plot Delta velocity versus mass (Figure 11). The way we break things down is shown in Figure 12. We have a Delta velocity and a specific impulse of 1,000 seconds when we calculated with our program. We come up with a payload of 36 metric tons, the thrust is 315 kilo-Newton. That’s about 70,000 pounds or so, including the mass of the shield. This is the output. I must say this mass ratio is not payload fraction. Payload fraction is shown in Figure 13. This is for the top curve, the heaviest vehicle that we got and that’s almost a half a million kilograms there. Pretty big stuff!

Looking at it parametrically in terms of payload fraction, we show that, as you demand more and more velocity out of a fixed performance, your vehicle becomes almost like the chemicals we have today, which have something like three to four percent payload fraction. This says that what you want to do is increase the specific impulse. And by the way, if you go to a single stage Delta V, which is like nine to ten kilometers per second with a nuclear vehicle, you begin to approach 25 percent of payload fraction.

I was talking to airplane people who design airplanes being flown for money and they say that of their takeoff weight, fuel is something like 40 percent. What we would like to do is drive the space vehicles in that direction.

We didn’t do anything on cost for this workshop, but we did a lot of work on cost back in the 1970’s. There is a whole bunch of reports that I sent NASA, and one written on February 1973 cost data, 1973 dollars. Oh, do they look good. I suggest that you take that to Congress when you go and talk to them.
Acknowledgments

The development of the PeBR for electric and thermal nuclear propulsion missions has been performed by the University of New Mexico's Institute for Space Nuclear Power Studies. The System Trades and Performance Studies were performed at McDonnell Douglas Space Systems Company, Huntington Beach, CA; the contributions of T.M. Miller and J.F. LaBar are hereby acknowledged.


DESIGN TRADE STUDIES

- Propellant Tank Geometries
  - Weight
  - Volumetric Efficiency
  - Radiation Considerations

- Skirts and Interfaces

- Handling, Transportation and Launching Factors

- Reusable vs Expendable

- Refueling, Refurbishing

- Start, Shutdown, Restart Factors
  - Fluid Transients
  - Heat Soak Back
  - Post Shutdown Cooling

  — Performance Loss/Recovery

CONVENTIONAL TANK CONFIGURATION

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Figure 1

Figure 2
SHIELD WEIGHT REQUIREMENTS FOR
CONVENTIONAL TANK CONFIGURATIONS

Figure 3

Figure 4
RADIATION MAP

Figure 5

DOSE RATE AFTER SHUTDOWN

Figure 6
CLASS 1 SINGLE-MODULE HYBRID RNS

Command and Control Module (6 ft)
Forward Umbilical
Slosh Baffle
Integral Waffle
Tunnel
Intermodule Structure
Docking Interface
Liquid Level Sensors

Propulsion Module (60 ft)

Nerva

Propellant Module (103.4 ft)
Aps Nozzle
Spray Nozzle
Propellant Feed System
Thermal and Meteoroid Protection

SPACE TRANSFER VEHICLE DESIGN DATA

LEO to GEO With Return Payload Mass 36,000 kg
Mission Data:
Velocity Increment 9,000 m/s

<table>
<thead>
<tr>
<th>ROCKET ENGINE</th>
<th>CRYOGENIC (O2/H2)</th>
<th>NUCLEAR FISSION</th>
<th>FUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (kN)</td>
<td>400.3</td>
<td>902</td>
<td>71.7</td>
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<tr>
<td>Specific Impulse (s)</td>
<td>450</td>
<td>429</td>
<td>860</td>
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<tr>
<td>Burn Time (s)</td>
<td>3,675</td>
<td>1,650</td>
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<table>
<thead>
<tr>
<th>MASS BREAKDOWN</th>
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</thead>
<tbody>
<tr>
<td>PROPELLANTS</td>
</tr>
<tr>
<td>(kg)</td>
</tr>
<tr>
<td>Fuel (LH2)</td>
</tr>
<tr>
<td>Oxidizer (LOX)</td>
</tr>
<tr>
<td>PROPPELLANT TANK(S)</td>
</tr>
<tr>
<td>Total Volume (in³)</td>
</tr>
<tr>
<td>Mass (kg)</td>
</tr>
<tr>
<td>PRESSURIZATION (He system) (kg)</td>
</tr>
<tr>
<td>ENGINE         (kg)</td>
</tr>
<tr>
<td>MISCELLANEOUS  (kg)</td>
</tr>
<tr>
<td>TOTAL VEHICLE MASS (kg)</td>
</tr>
</tbody>
</table>

Figure 7

Figure 8
### SPACE TRANSFER VEHICLE DESIGN DATA

**LEO - GEO - LEO Mission**:  
Mpl = 36,000 kg; Delt V = 9 km/s; Burn Time = 3675 s

<table>
<thead>
<tr>
<th>ROCKET ENGINE</th>
<th>CRYOGENIC , 6 RL-10' s</th>
<th>NUCLEAR , 4 ALPHA 2's</th>
<th>FUSION , Me=12 (isp)</th>
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<tbody>
<tr>
<td>Thrust (kN)</td>
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<td>278</td>
<td>208</td>
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<tr>
<td>Specific Impulse (s)</td>
<td>450</td>
<td>860</td>
<td>2500</td>
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### MASS BREAKDOWN

<table>
<thead>
<tr>
<th>PROPELLANTS (kg)</th>
<th>Fuel (LH2)</th>
<th>Oxidizer (LOX)</th>
<th>Total Volume (m³)</th>
<th>Mass (kg)</th>
<th>He System (kg)</th>
<th>ENGINE(S) (kg)</th>
<th>MISCELLANEOUS (kg)</th>
<th>TOTAL VEHICLE MASS</th>
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</thead>
<tbody>
<tr>
<td>333,291</td>
<td>51,275</td>
<td>282,015</td>
<td>970</td>
<td>8,158</td>
<td>1,374</td>
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<td>1,937</td>
<td>10,849</td>
<td>1,828</td>
<td>10,270</td>
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<td></td>
<td>105,123</td>
</tr>
</tbody>
</table>

**Figure 9**

### MARS MISSION ΔV SUMMARY

- **TRANS-MARS INJECTION**: 4.71 km/s
- **MARS CAPTURE**: 9.03 km/s
- **TRANS-EARTH INJECTION**: 9.93 km/s
- **EARTH CAPTURE**: 7.20 km/s

**TOTAL**: 30.87 km/s

- **LAUNCH DATE**: 11 MAY 2018
- **TOTAL TRAVEL TIME**: 250 DAYS
- **MARS STAY TIME**: 30 km/s
TOTAL OTV MASS vs. VELOCITY INCREMENT

PELLET BED REACTOR NTR

![Graph showing TOTAL OTV MASS vs. VELOCITY INCREMENT for PELLET BED REACTOR NTR with specific values for M_p = 36 mt, 20 mt, and 10 mt.]

SAMPLE PELLET BED NUCLEAR OTV MASS BREAKDOWN

Input Parameters

- Delta V ($\Delta V$): 15,000 m/s
- Specific Impulse: 1000 s
- Payload Mass: 36,000 kg
- Thrust: 315 kN
- Engine Mass: 1,875 kg
- Shield Mass: 4,000 kg

Calculated Parameters

- Mass Ratio R: 4.611
- Propellant Fraction ($M_p/M_0$): 0.857
- Payload Fraction ($M_p/M_0$): 0.086
- Tank Volume: 5,249 m$^3$
- Burn Time: 170 min

Component Mass Breakdown

- Propellant ($H_2$): 364,568 kg
- Propellant Tank: 34,703 kg
- Thrust Structure: 649 kg
- Pressurization System (He): 4,365 kg
- Meteoroid/Thermal: 9,164 kg

Total Vehicle Mass: 455,324 kg